Photovoltaics Overview
Fiscal Year 2001

Office of Solar Energy Technologies
U.S. Department of Energy

Highlights

Research and Development ....PAGE 3

■ Achieved a CIGS solar cell with a measured efficiency of 21.1% under 14-sun concentration.

■ Demonstrated a 16.5%-efficient CdTe polycrystalline thin-film solar cell.

■ Deposited Si layers using hot-wire deposition in less than 3 minutes and measured the best voltage ever from such a cell.

■ Awarded new research contracts in the Thin Film PV Partnership to 19 universities and 14 companies.

■ Demonstrated with Spectrolab a 34%-efficient GaInP/GaAs/Ge cell under 600 suns of concentration.

■ Sponsored 11th Workshop on Crystalline Silicon Solar Cell Materials and Processes to promote exchange of research results.

■ Selected seven university proposals for 3-year funding to perform basic research in crystalline silicon materials.

■ Awarded research contracts for non-conventional solar electric technologies—PV Technologies Beyond the Horizon.

■ Sponsored HBCU internship program and American Solar Challenge car race for university students.

Technology Development ....PAGE 10

■ Received final reporting of work under previous subcontracts awarded under PVMaT solicitations.

■ Initiated a new solicitation, *Photovoltaic Manufacturing R&D—In-line Diagnostics and Intelligent Processing in Manufacturing Scale-Up*.

■ Transferred the PV reflectometer to industry for use on production lines to measure key qualities of materials being fabricated.

■ Developed a six-step strategy for multilayer accident prevention and hazard management in PV manufacturing facilities.

■ Continued module and system tests outdoors and in the laboratories of the NCPV and its partners.

■ Sponsored a workshop, Moisture Ingress and High-Voltage Isolation for PV modules and cells.

■ Developed a new technique to study the moisture ingress properties of PV module encapsulants.

■ Demonstrated a non-destructive technique using ultrasonic detectors to characterize solder bonds in PV modules.

Systems Engineering and Applications ....PAGE 16

■ Sponsored the Photovoltaic System Symposium and drafted *PV System Reliability Research Plan*.

■ Measured the performance and safety of small stand-alone systems for rural applications.

■ Calibrated equipment to be used in certification programs.

■ Completed the phased research and product development program known as PV:BONUS

■ Provided technical assistance to promote PV for rural utilities.

■ Continued activities to promote international markets.

Front cover photos

Clockwise from top right, ending in center:

Solar panels supply electricity to the Metcalfe Federal Building in Chicago, IL, as part of a project promoted by U.S. Environmental Protection Agency, General Services Administration, Department of Energy, and private industry. Patrick Engineering/PIX09514

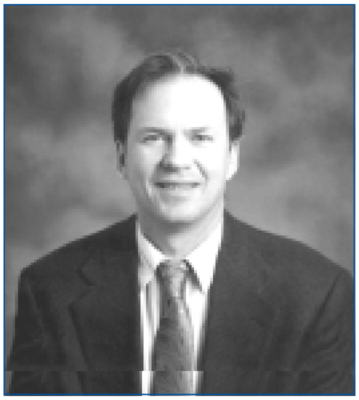
The American Solar Challenge 2001 solar car race allowed university students to hone their design and engineering skills, as well as their on-the-road strategies along 2300 miles of Route 66 from Illinois to California. The previous solar car race in 1999—then called Sunrayce—began in Washington, D.C. (shown here) and headed south to Florida. Byron Stafford/PIX08953

This photovoltaic system delivers electricity to the Indian Pueblo Cultural Center in Albuquerque, NM, with NCPV engineers at Sandia monitoring system performance. Sandia/PIX09714

Southface Energy Institute, in Atlanta, GA, serves to educate architects, engineers, and builders about advanced energy technologies in buildings. The photovoltaic roof shingles were developed by United Solar and Energy Conversion Devices under DOE's PV:BONUS program. John Haigwood/PIX04577

An NCPV researcher monitors the operation of an X-ray diffraction system, which measures structural characteristics of photovoltaic films produced by the CdTe Team at NREL. Warren Gretz/PIX10120

OUR VISION IS BECOMING REALITY



The value of solar electricity to our nation is more clear now than ever before. Solar electricity is available even when large power plants or electrical transmission grids are not. Solar electricity continues to flow even when petroleum or gas supplies are disrupted. Solar electricity can be generated and used where the power is needed. And solar electricity is generated by systems manufactured in a domestic industry whose continued growth will be unaffected by world events.

This year, for the third year in a row, the solar electric market grew at more than 30%. Fueling this growth is the U.S. photovoltaic (PV) industry—the companies that design, manufacture, install, operate, and maintain all components of solar generating systems. To help ensure a steady growth of 25% per year, the U.S. PV industry published *Solar Electric Power: The U.S. Photovoltaic Industry Roadmap*. The culmination of nearly 2 years of effort, the U.S. PV industry roadmap details the steps necessary to be sure that technical, market, and institutional activities continue supporting the industry's growth.

The messages of the U.S. PV industry roadmap are taken very seriously by the U.S. Department of Energy's (DOE) Office of Solar Energy Technologies, which manages the Photovoltaics Subprogram along with two other subprograms, Concentrating Solar Power and Solar Buildings. Achieving industry's goals will demand aggressive work in fundamental and exploratory research, manufacturing, and system applications to reduce the cost of solar electric systems. The research and development (R&D) accomplishments outlined in this document are testimony to the close cooperation the Solar Program has maintained with industry over the years. In fiscal year (FY) 2001, DOE's Subprogram was rated "outstanding" by peer reviewers for its effective use of performance-based contracts, promotion of public/private partnerships, and careful direction of taxpayer dollars for R&D of solar electric systems.

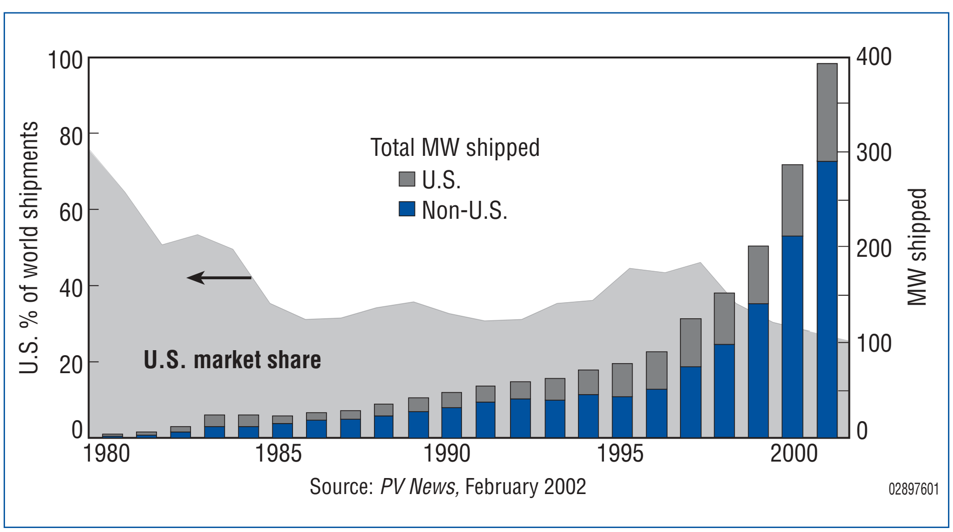
...success will depend on the direction, resources, scientific and technological approaches, and continued efforts of the "best and the brightest" among industry, the federal government, research organizations, and our educational institutions.

The U.S. Photovoltaic Industry Roadmap

Continuing the successful strategies of recent years, addressing specific issues identified by industry, and preparing for unexpected breakthroughs, the PV Subprogram plans to update DOE's 5-year plan every 2 years. This plan sets milestones—the metrics by which we measure our progress—for basic research, manufacturing research, systems engineering, and market development. Close cooperation with our partners in industry, research institutes, governments, and universities will help ensure that solar electric systems contribute even more to our energy security by providing a distributed, renewable, and wholly domestic energy supply.

Richard King

Richard King, Team Leader
Photovoltaics Subprogram
Office of Solar Energy Technologies
U.S. Department of Energy
Washington, D.C.



Annual world PV shipments showing U.S. and non-U.S. production (in megawatts [MW]). Percent of U.S. market share is shown in light gray in the background.

INTRODUCTION

The "photovoltaic effect" produces direct-current electricity, while using no moving parts, consuming no fuel, and creating no pollution. *The U.S. Photovoltaic Industry Roadmap*

The first PV device to actually generate electric power using light was made in 1954. Those early cells converted between 1% and 2% of sunlight to electrical energy. The efficiency of today's best solar electric cells rose in 2001 from 32% to 34%. Efficiency is calculated by dividing the amount of electrical energy produced by the light energy shining on the cell. Efficiency is an important benchmark for laboratory and manufacturing research in PV technology.

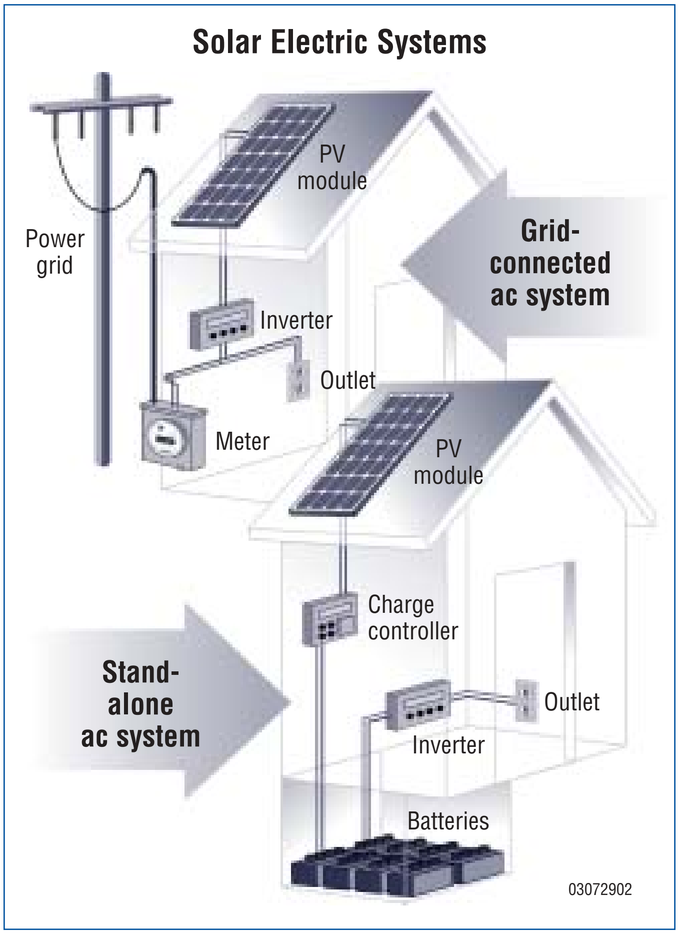
If efficiently tapped, the solar resource striking the earth could supply all our electricity needs. For example, a square region in Nevada measuring less than 90 miles on a side covered with solar electric modules that are 10% efficient would generate enough electricity to meet all U.S. energy needs. If efficiency improves, the area required decreases. Increasing efficiency to 11% results in a 10% reduction in the area required to provide this same amount of electricity.

It is equally important to note progress to reduce the cost of electricity generated with solar cells. Increasing efficiency plays a part in reducing cost, but so do improved manufacturing techniques, reduced material costs, and increased lifetime and durability of all system components.

Commercial use of solar electric cells began in 1958, when the Vanguard 1 satellite carried PV cells to power a 5-milliwatt backup transmitter. Today, virtually all satellites and spacecraft use solar cells to generate their electrical power. Interest in making PV technology affordable for terrestrial use was sparked by rising energy costs in the mid-1970s. Since then, the federal government, working with universities and industry partners, has conducted an aggressive R&D program to expand the use of this promising technology.

The DOE-sponsored R&D activities on generating electricity with solar energy accelerate the development process in several ways. Fundamental research supports creation of materials and devices, manufacturing research moves technology from the laboratory to the marketplace, systems engineering improves product performance and reliability, and market development activities improve the information available to users.

The PV Subprogram carries out these activities through the National Center for Photovoltaics (NCPV), an alliance of organizations working with the U.S. PV industry to maintain our global leadership position. Several national laboratories—the National Renewable Energy Laboratory (NREL) in Golden, Colorado; Sandia National Laboratories (Sandia) in Albuquerque, New Mexico; and Brookhaven National Laboratory in Upton, New York—are key participants in these efforts.



*A **solar electric system** includes several key components that work together to deliver electricity to the user. **Cells** are composed of layers of semiconductor and other materials that produce electric current in response to sunlight. Individual cells are connected in strings to make up the **PV module** that is sealed from the weather with encapsulants. Module electrical wires are connected by **electrical junction boxes**. PV modules generate direct current (dc) electricity that can be stored in **batteries**. **Charge controllers** keep batteries from overcharging or undercharging. If alternating current (ac) is needed, such as for conventional appliances or for interconnection to a utility grid, an **inverter**, or **power conditioner**, is necessary.*

Research and Development

…next-generation photovoltaic devices and products are vital for meeting future energy needs and maintaining U.S. leadership. *The U.S. Photovoltaic Industry Roadmap*

While continuing to improve the technologies in use today, the PV Subprogram is also investing in work to increase our number of scientific discoveries for the next generation of solar conversion devices. Today's promising commercial products are based on discoveries in amorphous silicon (a-Si) in the 1970s, copper indium diselenide (CIS) and cadmium telluride (CdTe) in the 1980s, and III-V multijunction devices in the 1990s. Work continues to develop the science necessary to take full advantage of these discoveries. Key vehicles for coordinating this work are the national research teams assembled and coordinated by the NCPV. In addition to work by these teams of experts from national laboratories, industry, and university centers, the DOE Solar Program has several initiatives under way to help generate revolutionary discoveries—High-Performance PV Research, Future Generation PV, and PV Beyond the Horizon.

Thin-Film PV Research

One of the early advances with the potential to reduce the cost of electricity from solar cells was the technique of applying thin layers of semiconductor material to inexpensive substrates such as glass. Today, three of these technologies, which use a-Si, CIS, and CdTe, are being fabricated by the PV industry in pilot plants or first-time manufacturing lines. The first commercial systems using these materials have been installed, and their performance is being monitored.

Copper Indium Diselenide and Alloys

Lightweight, flexible solar electric modules are being used by the U.S. Army and Marine Corps for field power packs. The higher the efficiency of these CIS modules, the more power they can provide for the weight. In addition, higher efficiency modules could compete with a-Si materials for incorporation into roof shingles that generate electricity. Global Solar Energy of Tucson, Arizona—a joint venture between Tucson Electric Power and ITN Energy Systems of Littleton, Colorado—set a new world record for a lightweight, flexible, thin-film copper indium gallium diselenide (CIGS; $CuInGaSe_2$) module. For this participant in the Thin Film PV Partnership Program, NREL verified an aperture-area efficiency of 9.2%, measured under the large-area continuous solar simulator at its Outdoor Test Facility. The previous best efficiency verified by NREL was just above 5%. Global Solar Energy has worked with the NREL CIS Team, the Measurements and Characterization Group, the National CIS R&D Team, and the Institute of Energy Conversion at the University of Delaware in the modification and testing of these CIGS modules.

To push efficiencies higher in thin-film devices, researchers modify the layers of materials that interact in the device to produce the photovoltaic effect. The Institute of Energy Conversion, University of Delaware, Newark, achieved a 16.9% efficiency for a thin-film solar cell with a new $Cu(InAl)Se_2$ absorber layer on a high-efficiency cell design. The new layer was deposited on a glass substrate coated with molybdenum at 530°C. The new cell design replaces gallium (Ga) with aluminum and may overcome the efficiency-limiting properties of Ga at high concentrations.

Eliminating another ingredient, the chemical-bath-deposited cadmium sulfide (CdS) layer, can allow more current to be collected and can reduce the complexity of deposition processes. In FY 2001, NCPV researchers achieved a 15.7%-efficient CdS-free CIGS solar cell—the highest ever for such a structure. To achieve this level of efficiency, researchers used a Cd solution to dope the surface region. Industrial partners who work with CIS materials are very interested in this finding because a Cd solution can be used repeatedly in manufacturing, whereas a CdS bath must be discarded after every use.

Global Solar Energy/PIX10802

Research continues to increase the efficiency—and therefore the power output—of flexible solar electric modules like these used by U.S. Army soldiers and Marines.

Siemens Solar Energy/PIX10803

This 12-kilowatt (kW) array of CIGS thin-film modules is one of several systems sold by Siemens Solar Industries. The company is expanding its production line (the only one in the world for this material) from 700 kW per year to multimegawatt-per-year production.

One way to reduce the cost of electricity from a solar generating system is to use inexpensive lenses to concentrate the sunlight. Thin-film solar cells are being designed and tested for operation under direct sunlight and for operation in such concentrating systems. In FY 2001, NCPV researchers achieved a CIGS solar cell with a measured efficiency of 21.1% under 14-sun concentration. The previous efficiency for this device structure was 18.5%. Work will continue to vary key process controls of this ZnO/CdS/CIGS thin-film device structure.

Cadmium Telluride

Since the earliest attempts to use CdTe materials, researchers have made variations in the basic device structure of SnO_2/CdS/CdT layers to achieve laboratory cell efficiencies around 15% and efficiencies up to 10% for commercial-scale modules. In FY 2001, a 5-year effort demonstrated a 16.5%-efficient CdTe polycrystalline thin-film solar cell at NREL. To improve the efficiency and reproducibility of this cell, researchers developed novel materials, revised the device structure, and developed a manufacturing process. One of the key changes applied results achieved in another part of the DOE research program to improve the performance of the transparent conducting oxide (TCO) layer. Another change integrated a zinc stannate buffer layer into the CdTe cells that improved performance and reproducibility. Finally, the team, which included 16 NREL researchers, developed and demonstrated a novel manufacturing process for fabricating solar cells with the new structure. This final step is important to ensure that high laboratory efficiencies can be reproduced relatively quickly by industrial partners, thus moving better products to market.

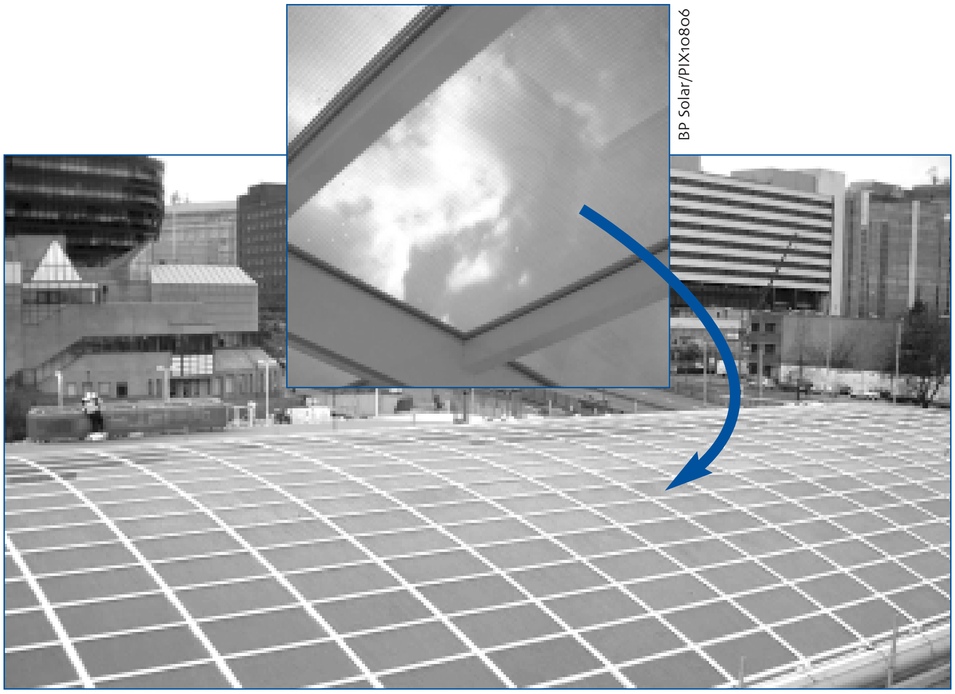
Another important parameter for commercial solar electric modules is power output. As part of its work with the Thin Film PV Partnership, BP Solar delivered CdTe modules that produced 90 watts (W) during performance tests at the NCPV. This is a new power output record for a thin-film module. Reliability testing, both indoors and outdoors, will continue as part of the product development effort.

Amorphous Silicon

One way to reduce the cost of commercial modules made of a-Si is to increase the rate at which high-quality semiconductor materials can be deposited on the glass substrate. In FY 2001, the NREL Amorphous Silicon Team made a single-junction cell using the hot-wire chemical vapor deposition technique. The team deposited the Si layers in less than 3 minutes and measured the best voltage ever achieved from such a cell. This accomplishment exceeded the planned progress for FY 2001, and it paves the way for additional advances to speed deposition of quality semiconductor material. In a solar cell fully optimized for

BP Solar/PIX10804

This CdTe array, manufactured at BP Solar's plant in Fairfield, California, is the first of many expected from this factory.



BP Solar/PIX10806

BP Solar/PIX10805

This semitransparent version of BP Solar's a-Si product incorporates improvements, such as better utilization of both silane and germane, developed through participation in the a-Si National Research Team. As a result of these improvements, manufacturing costs fell 24% in FY 2001.

Best Large-Area, Thin-Film Modules (standard conditions, aperture area)

Company	Device	Size (cm²)	Efficiency (%)	Power	Date
BP Solar	CdS/CdTe	8,390	11.0	92.5 W	09/01
United Solar	a-Si triple junction	9,276	7.6 (stabilized)	70.8 W	09/97
Wurth Solar	CIGS	6,623	10.4	68.9 W	11/01
First Solar	CdS/CdTe	6,612	10.1	67.1 W	12/01
Matsushita	CdS/CdTe	5,413	11.0	59.0 W	06/00
BP Solar	a-Si dual junction	7,417	7.6 (stabilized)	56.0 W	09/96
Antec Solar	CdS/CdTe	6,633	7.0	46.7 W	11/01
Siemens Solar	CdS/CIS-alloy	3,651	12.1	44.3 W	03/99
Kaneka	a-Si/thin x-Si/glass	3,738	10.0 (est., stable)	38.0 W (est.)	09/00
Global Solar	CdS/CIS/foil	7,495	4.9	36.5	02/01
United Solar	a-Si triple	4,519	7.9 (stabilized)	35.7 W	06/97

Modules with greater power output represent advances in the efficiency of materials and devices and improvements in fabrication techniques to produce uniform material over larger areas.

current, this layer of material would be the top cell of a multijunction PV device composed of materials deposited at high rates. The new material also may be deposited on plastic substrates at low temperatures.

Continuing Research on Thin-Film Materials

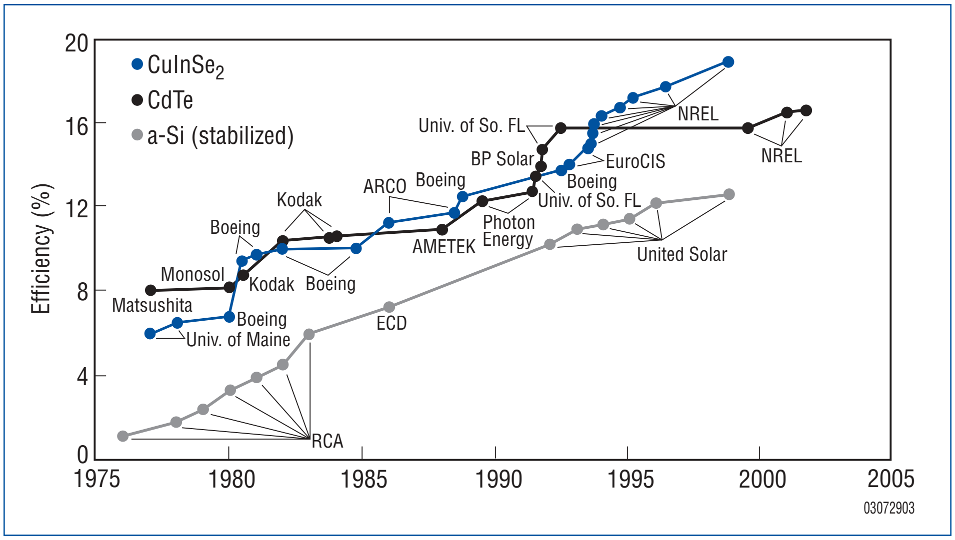
The solar electric products made of thin-film materials available today can trace their ancestry to the Thin Film PV Partnership, a DOE/NCPV program designed to accelerate the progress of this technology. About 6 years ago, the partnership, which was sponsoring cost-shared research contracts, organized national research teams at the suggestion of industry. These teams are made up of researchers from NREL, U.S. industry, and universities with expertise in each of these materials. About 40 researchers are on each team, doing the research and reporting on it approximately every 9 months. In 2001, a new team is using thin-film silicon in solar cells. This team will work closely with the existing a-Si research team, because some interests overlap.

Although products using thin-film materials are being sold, much needs to be done to improve understanding of the science behind these materials and devices. With improved understanding comes the ability to vary key parameters during fabrication, improve performance, and reduce costs. In FY 2001, the NCPV began awarding contracts for the next round of research to 19 universities and 14 companies, which will receive a total of $40 million in funding. The awardees will contribute a total of $13 million toward the effort.

The NCPV is making the awards in three categories:

Technology Partners awards are cost-shared with industry for projects to improve efficiency, reduce unit cost, and enhance product reliability of thin-film solar cells.

R&D Partners awards go to universities and businesses to increase understanding of the science behind the expanding solar electricity industry.



Best laboratory cell efficiencies for thin films

The *University Center of Excellence* award is designated by DOE for advanced research on solar-electric materials and devices, with the university at times working in partnership with industry groups.

The Thin Film PVs Partnership Program has prompted technical progress; activities under the program have received four R&D 100 Awards from *R&D Magazine*, as well as numerous patents. The next round of research will continue this momentum and help to solidify the U.S. position in the world market for new technologies.

High-Performance and Concentrator Research

Satellites and space communications use highly efficient solar cells based on multijunction gallium arsenide device structures developed under DOE PV research support. A promising way to use these high-performance solar cells on the ground is to use inexpensive lenses to focus sunlight from a large area onto a smaller area of solar cells. This approach allows solar cells to perform at a higher efficiency under the concentrated sunlight and requires smaller amounts of the precious solar electric devices.

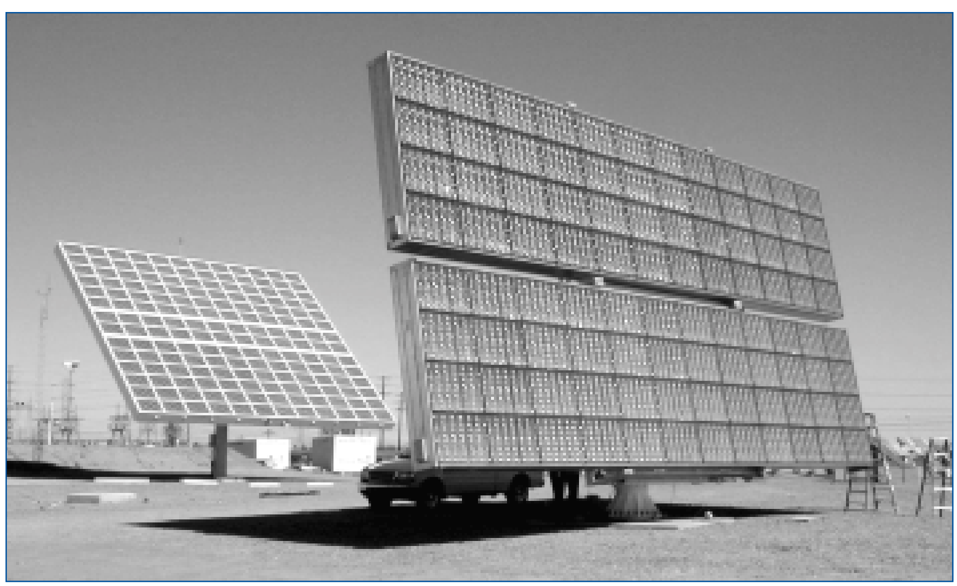
Researchers at Spectrolab, a major supplier of solar cells for space, work with the NCPV to increase the efficiency of triple-junction solar cells under concentrated sunlight for use in terrestrial power generation. In FY 2001, Spectrolab and NREL won an award from *R&D Magazine* for the triple-junction terrestrial concentrator cell.

Deemed one of the top 100 technological innovations of the year by the magazine, the best cell performed at 32.2% efficiency under 600 suns of concentration. Later in the year, Spectrolab improved the growth process and device structure for a 1-cm^2 cell that demonstrated 34% efficiency under 600-suns concentration.

Paving the way for wider use of concentrating solar electric systems, the NCPV engineers at NREL and Sandia, and in industry, have been working since 1992 to develop standards for testing such systems. In FY 2001, the Institute of Electrical and Electronics Engineers (IEEE) Standards Board approved the *Recommended Practice for Qualification of Concentrator Photovoltaic Receiver Sections and Modules*. Receiver sections and modules that pass these qualification tests conducted at the Photovoltaic Testing Laboratory at Arizona State University will have an advantage with consumers in this promising market.

To further advance the science behind high-performance solar cells, DOE awarded contracts in FY 2001 under the new High-Performance PV Initiative. The ultimate goal of this solicitation is to identify critical paths necessary to achieve a solar electric module with 33% conversion efficiency that would cost less than $1/W to manufacture.

Capitalizing on these developments in high-efficiency photovoltaic research, managers in DOE's



Amonix/PIX9174

After installing this high-concentration PV system totalling 300 kW in FY 2000, Arizona Public Service plans to begin testing a 500-kW system in 2002.

Concentrating Solar Power Subprogram are evaluating the feasibility of using concentrating PV converters as an alternative to thermal conversion devices such as Stirling or Brayton cycle engines.

Several analytical tools and test beds will be used to assess primary, secondary, and receiver optics. The High-Flux Solar Furnace at NREL will be used to test densely packed PV arrays. In 2002, the NCPV will sponsor the first international conference on concentrator technology.

Crystalline Silicon

In 2001, the NCPV sponsored the 11th Workshop on Crystalline Silicon Solar Cell Materials and Processes, at which more than 100 scientists and engineers from 22 companies and 27 research institutions discussed specific technical issues for research and manufacturing of crystalline silicon and thin silicon solar cells. These discussions are crucial to the design and conduct of the DOE PV Subprogram. For example, at the 10th Workshop on Crystalline Silicon Solar Cell Materials, solar cell companies identified areas of technical challenge that required fundamental research. By the close of FY 2001, NCPV reviewers had selected seven university proposals for 3-year funding to explore these very issues. The universities began their research and, with industry partners, formed four teams to explore: mechanical strength and yield; the production of better materials; hydrogen passivation and silicon nitride coatings; and contacts and selective emitters.

A technique for processing multicrystalline solar cells, developed at Sandia, is now available for licensing to industry. Known as reactive ion etching, this texturizing process has boosted cell performance by more than 10% over cells with a flat (reflective) surface. The process could also lead to thinner cells and reduced costs. In FY 2001, researchers at Sandia met with interested companies and worked with them to adapt the technique for individual products.

Institute of Energy Conversion—Center of Excellence (IEC)

The Institute of Energy Conversion (IEC), at the University of Delaware, has been a DOE University Center of Excellence in Thin Films since 1992. With the renewal of its status in 2001, IEC continues to furnish cutting-edge equipment and expertise to the PV research community.

For CIS materials, IEC optimized its own in-line (6-in.-wide) deposition system. In FY 2001, IEC investigated the formation of CIGS at various substrate temperatures and found that cells could be obtained with more Cu-rich CIGS absorbers at temperatures of 400°C rather than 550°C. IEC has collaborated on CIS materials with Global Solar Energy, International Solar Electric Technology, Siemens Solar Industries, UNISUN, the Florida Solar Energy Center, the University of Illinois, Washington State University, and the University of Oregon.

For CdTe materials and devices, IEC characterized CdS/CdTe interdiffusion, determined that transparent conducting oxide buffers increase cell performance when thinner CdS layers are used, and analyzed device stability under accelerated stresses. IEC collaborates with BP Solar and First Solar on CdTe research.

For a-Si solar cells, IEC studied the interactions of microcrystalline p- and n-layers with transparent conductive oxide contact layers. IEC has also succeeded in depositing 10-micron-thick polycrystalline films on glass using hot-wire chemical vapor deposition. IEC collaborates with NREL, BP Solar, the Georgia Institute of Technology, AstroPower, Inc., and others.

Measurements and Characterization

The NCPV is one of the few places in the world that provides independent verification of solar device efficiency for both small-area cells and large-area modules. In FY 2001, more than 16,000 measurements were taken for more than 110 collaborators. In addition, more than 2,300 standardized PV cell and module measurements were provided for NCPV researchers in industry, academia, and DOE laboratories.

Basic and University Research

Universities can focus on fundamentals and have access to a range of tools and expertise. The university is a meeting place for every science and engineering discipline necessary for breakthrough innovations. Material scientists work with process control experts, who work with optoelectronics researchers. Universities also produce the expert workforce needed for research, manufacturing, and development of PV products. University laboratories are thus well suited for exploratory research and the testing of new concepts. Their political neutrality and nonprofit status allows the exchange and publication of divergent, credible information.

Future Generation PV Technologies

In FY 2001, organizations working on the Future Generation PV subcontracts—to explore unconventional ideas for converting sunlight into electricity—began to generate results that industry found useful. For example, the University of Rochester achieved a very effective antireflection coating for thin-film silicon using a new process that creates a highly uniform film on any Si substrate. Using a simple electrochemical etching technique, the layer of porous Si had adjustable optical, electrical, and mechanical properties. Rochester is working with Evergreen Solar to help the company incorporate some of the techniques into its manufacturing line. Antireflection coatings that trap light could increase the efficiency of multicrystalline silicon solar cells.

PV Technologies Beyond the Horizon

Today's solar electric technology is based on breakthrough research conducted 30 to 40 years ago. There is reason to believe that there are many more revolutionary PV technologies beyond the horizon of our present knowledge, waiting to be discovered. The PV Beyond the Horizon initiative supports scientific research designed to lead to nonconventional PV technologies that might dramatically decrease the cost of electricity from the sun. Some of the research will explore entirely new materials or processes for generating electricity from the sun.

One new solar electric technology with the potential to provide low-cost electricity is the dye-sensitized solar cell. With foundations in photochemistry, rather than in the solid-state physics of today's commercial products, the dye cell has demonstrated efficiencies greater than 10%. An NCPV assessment of dye-cell technology concluded that the dye-sensitized solar cell could be developed into a cost-effective competitor with available solar electric technologies. Although this promising technology is relatively new and therefore high-risk, its potential warrants increased DOE support for research and development.

Georgia Institute of Technology—Center of Excellence

The DOE-funded University Center of Excellence in Photovoltaics at the Georgia Institute of Technology (Georgia Tech) has contributed to the understanding of silicon-based solar electric cells since 1992. The faculty and students at Georgia Tech fabricated devices that have set several world records for conversion efficiencies. In addition, Georgia Tech works with industry to improve manufacturing techniques. For example, the Rapid Thermal Processing (RTP) methods they pioneered are faster than conventional furnace diffusion and oxidation of silicon wafers by a factor of five or more.

In 2001, Georgia Tech investigated the impact of RTP on device performance, particularly in terms of emitter saturation current, back-surface passivation, contact resistance, and, for multicrystalline material, on gettering and hydrogenation. Overall, the combination of low emitter saturation currents and improved performance from RTP shows that the processing technique can produce high efficiencies in multicrystalline silicon material while lowering manufacturing costs.

Sara Barba/PIX10162

The University of Michigan's solar car, M-Pulse, crosses the finish line in Claremont, California, after racing 2,300 miles in the American Solar Challenge 2001.

Competing for the Best Minds

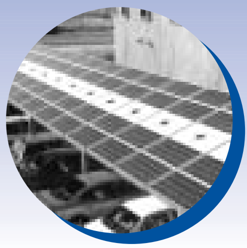
The DOE Solar Program sponsors several activities that encourage college students to pursue a career in solar energy research. In 2001, the program again supported the American Solar Challenge, an intercollegiate competition to design, build, and race solar-powered cars across the United States. The 2,300-mile race of vehicles powered entirely by sunlight followed historic Route 66 from Chicago across highly varied terrain and climate to Claremont, California.

Every year, DOE and NREL also sponsor about a dozen undergraduates from historically black colleges and universities (HBCUs) to perform PV research, explore international applications, and fill summer intern positions at NREL. In 2001, a program review meeting was held in conjunction with the NREL Renewable Energy Academic Conference at Texas Southern University in Houston.

In 2002, another student challenge will be the Solar Decathlon, which consists of ten interrelated design competitions. Fourteen student teams will design, build, and operate houses powered only by solar electric systems. Students in architecture, engineering, marketing, communications, graphic arts, and computer science will work together on each team. The houses will be assembled and displayed on the National Mall in Washington in late September. The Solar Decathlon is sponsored by DOE, NREL, BP Solar, and the American Institute of Architects.

Additional Achievements in R&D

Organization	Achievement	Why it is important
West Virginia University, Notre Dame, and NREL	Developed low-cost method to etch a relatively uniform array of 4- to 10-nm-diameter holes (nanocolumns).	Method provides uniform arrays of nanostructures necessary for electrochemical fabrication of semiconductor nanostructures for high-efficiency solar cells.
University of Toledo	Used photoluminescence (PL) to find that PL signal in CdTe solar cells drops as cells are stressed by temperature and light.	Increases understanding of materials behavior to pave the way for future improvements in devices.
NREL	Prepared p-type TCOs in four materials systems: ZnO:NO, $CuInO_2$, Cu_2SrO_3, and $CuAlO_2$.	Previously, it was considered impossible to fabricate p-type TCOs. Opens possibility for novel solar cell designs using these materials.
NREL	Used hot-wire chemical vapor deposition to create a 4.1%-efficient (stabilized) a-Si solar cell with an i-layer deposited at 83 Å/s.	Best efficiency yet for deposition at this high rate indicates promise for hot-wire technique.
NREL	Filed patent application for novel multijunction crystalline silicon solar cell using isoelectronic doping of both the conduction and valence bands in GaP.	New material with variable bandgap can be fabricated to be lattice-matched to crystalline silicon, allowing much higher efficiency solar cells using silicon.
Crystal Systems and NREL	Grew and wafered small <100> dislocation-free Czochralski crystals from feedstock refined from metallurgical-grade silicon.	This method could produce an unlimited and low-cost source of silicon feedstock for future mass production.
United Solar Systems Corporation and NREL	Produced an 11.6%-efficient a-Si tandem solar cell at 10 Å/s deposition rate that loses 18% efficiency during stabilization.	New low degradation for a tandem device produced at this speed.
Northwestern University	Developed Sn-doped CdO films with conductivities five to ten times greater than those of conventional indium tin oxide TCO.	Promise of lower current losses, more efficient PV cells.
University of California, Berkeley	Fabricated self-aligning quantum structures.	Led to higher efficiency quantum structure solar cells.
University of California, San Diego	Demonstrated quantum-well structure with 1-eV GaInNAs material with a factor of two improvement in minority-carrier lifetime.	Could lead to a 40%-efficient cell for use in concentrator systems.



Technology Development

Technological leadership is necessary both for economic competitiveness and to become a significant contributor to the nation's energy portfolio. *The U.S. Photovoltaic Industry Roadmap*

The growing U.S. PV industry is poised to benefit from cost-shared research on manufacturing. PV module shipments should exceed 400 MW for 2001, and the growing manufacturing capacity will exceed this amount in the years ahead. In 2001, the U.S. PV industry marketed about $1 billion of the world's $2.5 to $3.0 billion in product. To maintain technology leadership and market share, improvements in product must move from U.S. laboratories to the world marketplace.

Manufacturing Research and Development

Against this backdrop of a growing market, the PV Manufacturing R&D Project initiated a new solicitation, *Photovoltaic Manufacturing R&D—In-line Diagnostics and Intelligent Processing in Manufacturing Scale-Up*. This solicitation encourages teams to share the cost of high-risk research to develop intelligent processing for larger scale manufacturing that will be the foundation for achieving the goals set out in the *U.S. Photovoltaic Industry Roadmap*.

Since Congressional funding for manufacturing research and development began in 1991, great progress has been made in reducing the cost of PV systems and improving the performance and reliability of commercial products. Work under previous subcontracts awarded under PV Manufacturing Technlogy (PVMaT) solicitations were completed in 2001, just as the new set of contracts was awarded. A summary of each company's accomplishments follows. Final reporting will continue into FY 2002.

Specific R&D Problems in Product-Driven Manufacturing

The 14 subcontracts awarded in FY 1998 will total about $60 million over a 3-year period with 48% subcontractor cost-sharing. The following is a brief description of each of the 14 active subcontracts in FY 2001, including some of the accomplishments.

ASE Americas developed a new non-acid-based etching process and introduced this new process into manufacturing to strengthen the wafer, lessen silicon acid etching loads, and reduce waste products. The company completed the evaluation of lasers for cutting wafers with reduced levels of damage and has selected a candidate for manufacturing line trials. Efforts toward flexible manufacturing have resulted in full-capacity manufacturing of 10 cm x 15 cm EFG wafers. The company also completed preliminary testing of an improved encapsulant with superior transmission and better lamination characteristics and plans to evaluate it in full-scale manufacturing.

AstroPower increased the generation capacity of a Silicon-Film™ wafer-making system by 350%. The new sheet manufacturing equipment runs at 3.1 m/min and generates a continuous sheet that is nominally 8 in. wide. A single system has a capacity of 15 MW per year. AstroPower also designed, commissioned, and qualified a new in-line, continuous, phosglass HF etch system in solar cell production. In addition, the company designed, developed, and installed a continuous in-line silicon wafer NaOH etch system, and initiated testing in production. Both systems will contribute to reduced costs, increased throughput, and improved safety.

Crystal Systems reported achieving the goal of reducing metallic impurities and boron to less than 1 part per million atomic (ppma) and phosphorus to less than 10 ppma for a 60-kg Si charge size. Achievement of less than 1 ppma of boron by this simple refining technique is a breakthrough toward the goal of achieving low-cost solar-grade silicon for PV applications. The projected production cost of solar-grade silicon is less than $10/kg.

Energy Conversion Devices (ECD) developed and installed a new plasma-enhanced chemical-vapor deposition (PECVD) cathode deposition geometry, decreasing down-web deposition nonuniformity from about 50% to about 5% for the company's 5-MW production machine. ECD also developed a new PV Capacitive Diagnostic System that reduces the delay between production and characterization by more than a factor of 100. The system is already being used in production as an essential QA/QC device. Both of these advances will be implemented on ECD's 25-MW production equipment.

Evergreen Solar has focused efforts in the areas of crystal growth automation, cell and module manufacturing automation, and material handling and process flow development. A redesign of the crystal growth furnace was completed. It includes an 8-cm-wide ribbon, an increase in growth rate, and a newly developed automatic thickness control mechanism. Additionally, the hot-zone consumable costs were reduced by 60%. Cell manufacturing automation resulted in a streamlined process. The streamlined process includes no prediffusion etch, no conventional carriers, wafers held horizontally in specially designed boxes for high-density storage, and generic components installed on all automated machines. The addition of a plasma nitride process resulted in a 12% to 13% cell efficiency.

First Solar increased laser scribing speed from 70 mm/s to 1700–3000 mm/s, achieving a throughput rate of 60 modules/h per laser system of three systems using a new type of high-frequency, low-pulse-width, galvanometer-driven laser beam system. This has decreased the cost per system by a factor of two and decreased significantly the kerf and spacing of the scribe lines, thereby increasing the active module area. The scribing station is now completely automated.

Global Solar Energy demonstrated monolithic integration methods and equipment for a high-speed, all-laser process for CIGS module fabrication on flexible substrates. Total interconnect widths of less than 300 microns (µm) have been achieved using multiple beams at scribing rates of 30 cm/s. Modules composed of more than 1000 monolithic interconnects with open-circuit voltages approaching 300 volts (V) have been produced. This enables this technology to achieve high-speed, all-laser monolithic integration with very small interconnect area loss for the large, high-voltage, high-efficiency, low-cost modules needed by utilities and large users for bulk power generation.

The Omnion Power Engineering Corporation subcontract was terminated with a mutually agreeable "No Cost Termination." This is the result of changing priorities by Omnion following its purchase by an electrical switching company. No FY 2001 funds were expended on this subcontract.

PowerLight Corporation reduced installed system costs for very large systems to $3.80/W. Improvements contributing to this reduced cost include increased production line throughput of the cement-coated extruded polystyrene substrate from 3 minutes per tile to 45 seconds per tile and automation of the spacer (surface for mounting PV module on the tile) attachment process for consistent positioning spacers, and 20 seconds per tile throughput. Additional contributing improvements include better methods for placement of the PV module on the spacers; speeding placement from 120 seconds per tile to 50 seconds per tile with better ergonomics; and more accurate alignment and development of a trimming process, reducing required labor 75% and improving the overall quality of the tile edge.

Schott Applied Power (formerly Ascension Technology) worked on the SunSine™300 AC module for improved performance, lower cost, and improved manufacturability. Production costs were reduced by 32%. Pilot production and production runs were completed. Resulting products have been sold. Overall inverter size was reduced by 26%, and inverter efficiency was increased to 88%. Soft-switching technology was incorporated.

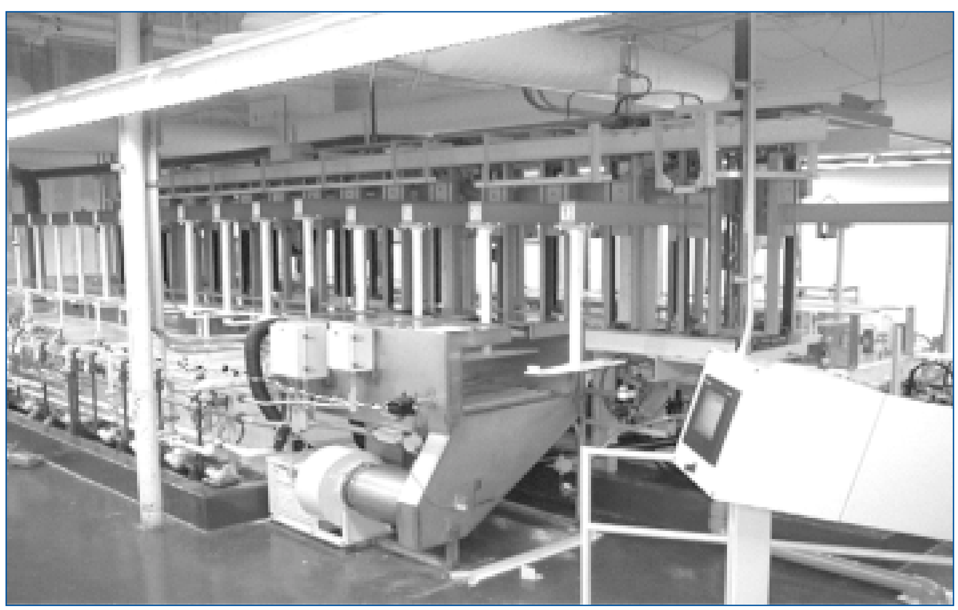
Siemens Solar Industries achieved production of 195-micron solar cells with an average efficiency of 16% (17% peak efficiency) using a boron back-surface field and thin grid lines. The company also reduced caustic waste released to the environment by nearly 80% over two years. Siemens completed the development and transfer of tooling to its production line for the manufacture of 200-mm cells.

BP Solar (formerly Solarex) established a process and the equipment for casting using variable-piece-size silicon feedstock. This significantly increased the availability of silicon feedstock. BP also developed a high-efficiency PECVD Silicon Nitride Process and implemented it in a cell production line. On Solarex polycrystalline silicon, this process increased the cell efficiency by 6% over the standard TiO_2 antireflection-coated cells.

The company also verified that the sodium reduction of silicon tetraflouride produces a silicon matrix material. This is the first step in the effort to produce a solar-grade silicon feedstock.

Spire Corporation has focused its work on developing cost-effective, automated, flexible post-lamination processes for PV module assembly. Under this subcontract, the company developed (1) a module buffer storage system, including conveyor load/unload and elevated storage; (2) an automated edge trimming system; and (3) an integrated module test system that combines high-voltage isolation testing with module performance testing. The automated edge trimmer has just been completed in its second phase and is now being shown to the PV industry. The development and implementation of these automated systems is expected to result in significant labor cost savings and increased throughput.

Utility Power Group (UPG) completed the development of a factory-assembled PV Array Power Unit



Siemens Solar Industries/PIX10807

Siemens Solar Industries and NREL received an award from the Federal Laboratory Consortium for Technology Transfer for work to improve manufacturing in this facility. By developing a technique to reprocess oils and solvents used in cleaning and etching silicon wafers, the company decreased by nearly 80% over two years the amount of caustic wastes from PV manufacturing that enter the environment.

Warren Gretz/PIX09671

Measuring key parameters without touching the material, NREL's PV reflectometer is now being used on the fabrication lines of several companies to measure key qualities—such as surface roughness, antireflection coating thickness, metallization fraction and height, and back-side reflectance—of materials being fabricated. This ultra-fast, electro-optical diagnostic technique does not interfere with the speed of processing. Researchers at NREL initially used the device to test material samples from industry. Through the NCPV and national research teams, this tool is now available to industry.

for rooftop applications. The installation and miscellaneous balance-of-systems costs (other than power conditioning and storage) totaled $3.95/ft^2$. In a test for planned projects for Sacramento Municipal Utility District (SMUD), UPG reported a crew of two installed 1 kW of PV on a test roof in less than 1 hour.

Only ASE Americas requires FY 2002 funding. The rest of the subcontracts from the FY 1998 solicitation are complete.

Environmental Safety and Health

A myth persists that even though solar electricity generation is clean, PV manufacturing is a polluting industry. In reality, some 80% of current PV manufacturing is silicon-based, having the same processing and risk as the semiconductor industry. These manufacturing companies all abide by the same codes, controls, and laws that regulate and oversee operations of a world-class semiconductor company.

Wanting to ensure continued safety, DOE enlisted specialists at Brookhaven National Laboratory's National Photovoltaic Environmental, Health, and Safety Assistance Center to audit manufacturers on a voluntary basis, to head off any environmental, safety, and health concerns before new products and processes reach mass-production scale. Brookhaven monitors DOE's research contracts and responds to requests from the NCPV. For example, Brookhaven investigated the issues surrounding the new technology of dye-sensitized solar cells, and published papers on the disposal and recycling of various types of solar cells. In 2001, Brookhaven specialists consulted with BP Solar, First Solar, Siemens Solar, ASE Americas, the Electric Power Research Institute, and the California Energy Commission to develop a six-step strategy for multilayer accident prevention and hazard management in PV manufacturing facilities.

Module and Array Performance and Reliability

To reach the goal of cost-competitive solar electric products with a 25-year service life, the NCPV has assembled a team consisting of scientists and engineers at NREL, Sandia, the Southwest Technology Development Institute (SWTDI), the Florida Solar Energy Center (FSEC), and the Photovoltaic Testing Laboratory at Arizona State University. A complex combination of laboratory tests, accelerated tests, field tests, destructive tests, and model development is used to provide the PV industry with the information needed to manufacture products intended to meet DOE's goal of 25-year service lifetimes.

To reach the PV Subprogram's goal, solar electric systems must withstand year-round weather conditions for more than a quarter of a century—

NREL Outdoor Test Facility

NREL maintains the state-of-the-art Outdoor Test Facility (OTF) to test performance and reliability of solar electric cells, modules, and small (1–5 kW) systems. These tests yield crucial information for industry and universities that are setting research goals. The OTF also calibrates primary reference cells for use in house, by other national laboratories, by industry, and by universities. It is one of four world facilities certified to calibrate in accordance with the world photovoltaic scale.

Researchers at the OTF measure performance in actual outdoor tests and using solar simulators indoors. Indoors at the OTF, modules are tested for failure and performance in conditions of high voltage, high heat, high humidity, flexing, static loading, and simulated hail strikes.

Outdoors, test beds at the OTF measure long-term performance and stability. More than 30 modules can be monitored over weeks, months, or years; and more than 50 modules can be tested for short-term performance under prevailing weather conditions. Two test beds perform stress tests of modules under accelerated conditions of high voltage and high sunlight concentration. Seven grid-tied, 1- to 2-kW systems are maintained to test modules made of varied materials for long-term performance and reliability. Stand-alone systems for remote homes and street lights are also being monitored.

Technical details on all testing are available at ***http://www.nrel.gov/ncpv***

Testing at Sandia

Sandia conducts module performance and durability studies for manufacturers based on data from several test sites. For new modules or for ones that have operated in the field for years, researchers collect data on electrical performance, extent of delamination, integrity of solder joints, and properties of encapsulants. Tests include outdoor electrical performance, dark current-voltage (I-V), infrared (IR) imaging, ultraviolet (UV) inspection, solder-joint metallurgy, and ultrasonic characterization, as well as destructive testing for specific failure modes.

An inverter test facility provides surge testing and accelerated life testing. A new 30-kW hybrid test bed for inverters is designed for grid-connected or stand-alone PV systems.

In FY 2001, Sandia designed and began operation of a Distributed Energy Test Laboratory (DETL) that includes a 75-kVA microturbine; a 90-kVA diesel; and load banks that are resistive, inductive, and capacitive in nature. The product of an agreement with the Salt River Project and Sandia, this DETL can be used to study the effects of distributed generation system (including PV and PV hybrid systems) on electrical utility operation.

Technical details on all testing at Sandia are available at ***http://www.sandia.gov/pv***

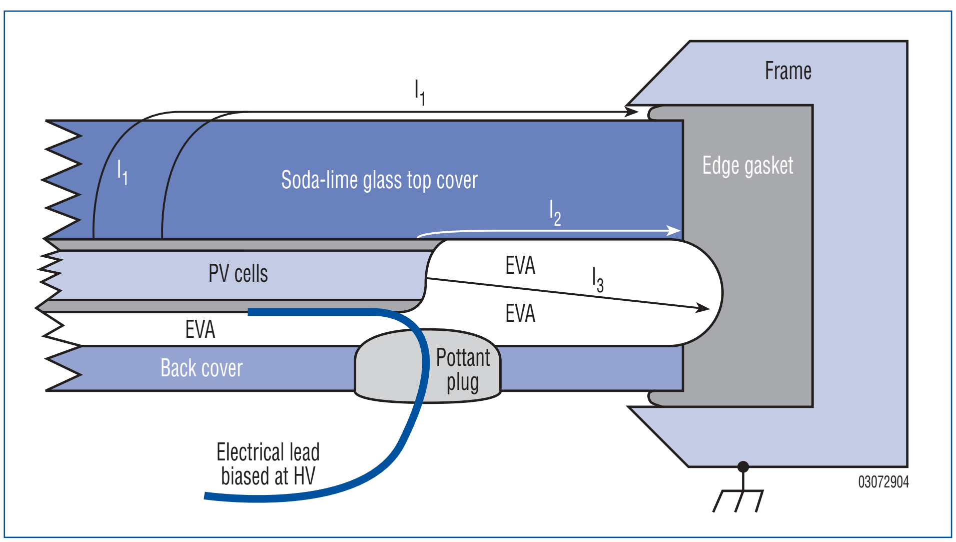
intense sunlight, high humidity, driving rain, snow, and hail—as well as temperatures from well below zero to midday summer heat. One effect of long-term exposure to weather is the intrusion of water into the module and cell structure. Besides the loss of electrical efficiency that results from current drain, moisture intrusion has been linked to durability problems, such as corrosion of solder joints. These reactions to moisture inside modules reduce the electrical performance of PV systems. To address this aspect of module reliability, NREL and Sandia cosponsored a workshop entitled Moisture Ingress and High-Voltage Isolation. The 45 participants from 15 companies and 4 laboratories discussed the packaging needs of solar electric modules made of crystalline silicon and thin-film materials. The participants in these workshops furnished valuable guidance on research needed to improve the durability of solar modules.

In FY 2001, NCPV researchers conducted tests that manufacturers requested on modules in which performance had deteriorated after several years of operation in the field. Tests conducted at the Module Long-Term Exposure program at FSEC and SWTDI, as well as module exposure activities at NREL and Sandia, contribute to durability information. For example, in 2001, Sandia recharacterized a group of commercial modules exposed for about 3 years at FSEC and SWTDI. Performance tests on the modules were compared to records of test results made before the modules were deployed in the field.

It is now possible to measure the water vapor transmission rates of solar electric module back sheets and encapsulants at elevated temperatures, thanks to a technique developed and demonstrated at NREL in FY 2001. This unique capability will allow NREL, in collaboration with manufacturers, to study the moisture ingress properties of various solar electric module encapsulant materials.

In another study, a 3-year accelerated test of solar electric modules rated for high-voltage operation was conducted at the High-Voltage Test Bed at NREL. The results were published in FY 2001 so that manufacturers can design modules that have up to 30-year service lives and are rated for high-voltage applications. A similar high-voltage test capability was established at FSEC during FY 2001 to test high-voltage isolation characteristics in a high-humidity environment.

The solder joints that connect conducting ribbons to PV cells must last 25 years, if the program goal is to be met. When solder joints deteriorate, electrical output declines or stops altogether, causing module failure. Tests of modules that have operated for up to 20 years show that some manufacturing techniques produce more robust solder joints



This cross-section of the edge-seal region of a thin-film module illustrates the complexity of designing a system to keep water out of solar electric modules. EVA is ethylene vinyl acetate.

than do others. In FY 2001, metallurgical studies of dismantled modules have yielded useful information to manufacturers. In addition, new nondestructive techniques incorporating ultrasonic detectors were used at Sandia to characterize solder joints between the copper ribbons that connect cell strings inside AstroPower's modules. When perfected, such techniques could be incorporated into manufacturing lines or used in the laboratory to verify the quality of products in the field.

Important tools for system designers are the models of module performance being developed by the PV Subprogram. Using data from many sources, including real-time data collected at the Performance and Energy Ratings Test Bed at NREL, researchers at NREL and Sandia develop these models, as well as databases of actual performance, for commercially available products. Measuring performance helps assure consumers that nameplate ratings of products correctly reflect the performance they can expect. The performance characterization reports completed in FY 2001 at Sandia for seven manufacturers have been incorporated into the database of module performance parameters.

Sandia/PIX10808

Experimental optimization of stand-alone photovoltaic systems based on ac-energy production has been made possible by integrating comprehensive module and array testing at Sandia with rapidly evolving system test procedures. Systems integrated by Energia Total, Ltd. (shown), Sacred Power Corporation, Kyocera Solar, and others are being optimized for performance and reliability.

Warren Gretz/PIX10748

Researchers at NREL's Outdoor Test Facility in Golden, Colorado, use advanced state-of-the-art laboratories and outdoor test beds to characterize the performance and reliability of PV cells, modules, and small (1- to 5- kilowatt) systems, such as this solar concentrator system.

The module and array performance model developed at Sandia was upgraded in FY 2001. The model has been validated through intercomparison studies with NREL, the National Institute of Science and Technology (NIST), and module manufacturers. Test results from more than 120 commercial modules are now included in the database that supports the model.

Balance-of-Systems Components Development

A key objective of the new solicitation for manufacturing R&D is to support improvement in balance-of-system components needed in addition to the solar cell modules to deliver electricity to the user. This improvement can come through better understanding of existing hardware and by developing improved equipment.

One very important component of a solar electric system is the inverter that converts the dc electricity produced by the modules into the ac used by everyday appliances and the electrical distribution grid. At the close of FY 2001, Xantrex Technologies, Inc., began work on a cost-shared contract to the NCPV, "PV Inverter Products Manufacturing, and Design Improvements for

Cost Reduction and Performance Enhancements." Xantrex is developing digital signal processing to upgrade its product line of power conditioning equipment. Under this contract, the company will design manufacturing approaches for 2-kW, 10-kW, and 20-kW inverters for connecting solar electric systems to the utility grid. The new products will meet all operational and safety requirements for use with utility systems.

Understanding how inverters connected to solar electric and other distributed generation technologies interact with the utility distribution line is crucial to utility acceptance of distributed generation systems. Utilities now require that inverters for PV systems and other distributed energy generators pass either the *IEEE 929-2000 Recommended Practice for Utility Interconnected PV Inverters* or the *UL 1741* standard. These standards were designed to ensure that any combination of inverters would not island. Because more PV systems are being installed on homes and businesses within each utility service territory and because new inverter designs are available, it is now even more important that the technical approaches in the standard be thoroughly validated. NCPV engineers at Sandia are conducting tests to ensure that several inverters on the same utility feeder line will recognize when the utility grid loses power. This work has been requested by BP Solar, Xantrex/Trace Engineering, and the large California utility, Pacific Gas and Electric Company.

Inverter tests are conducted at the inverter test facility at Sandia and at the flexible test bed at NREL. In FY 2001, Trace Engineering installed a Sun Tie 2500 inverter with a crystalline-silicon array at NREL, where a data logger will monitor the solar insolation, output current, voltage, and power. Trace will use these data to refine its product. Manufacturers who submit their new inverters to the Highly Accelerated Lifetime Testing (HALT) evaluations done under Sandia direction gain invaluable information about the durability of their design. Five inverter designs have been evaluated and the results supplied to the manufacturers. Inverter testing protocol is under development at Sandia for eventual use in an inverter certification program.


Sandia/PIX10809

At the Sandia test bed for balance-of-systems components, four parallel Xantrex Sun Tie inverters undergo a special test for islanding requested by BP Solar.

To improve the reliability of inverters, Sandia worked with industry in FY 2001 to draft an Inverter Reliability Initiative. The goal of this effort is to increase the mean time between failures of inverters from the current 5 years to at least 10 years. Hardware development contracts will be awarded after preliminary technical requirements for such an inverter are developed with input from an inverter manufacturer, a power electronics supplier, and a university research group.

Batteries operating with solar electric systems have special design and operation requirements. Standards relating to the use of batteries in renewable energy systems will remove a significant barrier to stand-alone or backup power systems. The IEEE Energy Storage Group will soon publish a guide for selecting and testing lead-acid batteries in stand-alone PV systems, a guide for using lead-acid batteries in hybrid remote area power supply systems, and a recommended practice for sizing nickel-cadmium batteries for PV systems. They can be used by designers, developers, and users of PV systems to select and size batteries for a wide range of applications. The standards will also help in estimating performance and guiding operation to achieve the best performance from batteries in PV systems. NCPV personnel from Sandia, battery manufacturers, battery users, suppliers of raw materials, and systems researchers participated in the standards-developing process.

Engineers at Sandia have tested five battery types from different manufacturers on the hybrid test bed and reported the results to the manufacturers. In addition, batteries in PV hybrid systems were tested on location at Grasmere, Idaho, and Mt. Washington, Vermont. The resulting reports document design requirements for high-reliability sites. Batteries are increasingly important because even grid-connected solar electric systems must have batteries if they are to operate as backup systems for utility power.

Systems Engineering and Applications

The U.S. electrical grid will increasingly rely on distributed energy resources in a competitive market to improve reliability and moderate distribution and transmission costs... *The U.S. Photovoltaic Industry Roadmap*

Solar electric systems connected to utility grids provide electric power where it is needed—at a home or business—without the need for transmission over long distances. Many solar electric systems today also supply power even when the utility grid is inactive. To reduce costs, enhance performance, and increase durability of solar electric systems for specific distributed applications, the PV Subprogram applies a systems engineering approach to design and testing. The activities also promote certification, deployment, and monitoring of PV systems in various applications to promote understanding of the benefits of PV for specific markets.

System Performance and Engineering

Systems engineering activities strive to ensure that each component is properly designed and that the components perform well together over the life of the system. Solar electric systems include many parts in addition to the PV cells and modules, and these other components are absolutely necessary for any benefit to accrue from the cells and modules being developed in the laboratory.

In FY 2001, the PV Subprogram sponsored the Photovoltaic System Symposium at Sandia, which was attended by more than 200 people from industry, government, utilities, and educational institutions. Participants shared diverse experiences in implementing PV projects and discussed a systems approach to meeting the 20-year production goals of the PV industry roadmap. Such an approach includes increasing reliability, improving performance, reducing life-cycle costs, removing barriers, and expanding markets.

Although manufacturers are now offering 10- to 15-year warranties on PV modules, PV systems that operate reliably for 25 years are the goal of the PV Subprogram. To reach that goal, DOE is supporting research and analysis using field data and models to identify areas for technical development. In FY 2001, Sandia drafted a *PV System Reliability Plan* in consultation with industry. The plan recommends continuation and prioritization of several activities already in progress such as: developing a reliability database to improve understanding of the performance of real systems; examining PV systems and components after extended operation in the field to identify sources of performance degradation or failures that could be prevented by changes in manufacturing; modeling system performance to identify fault-tolerant designs, sensitivity to component failure, and cost-effective component replacement strategies; and working with industry and users to resolve technical or institutional barriers to system reliability.

Evaluating and improving system performance was the objective of research, completed in FY 2001, that measured the performance and safety of small stand-alone systems for rural applications; calibrated equipment to be used in certification programs such as the new program at FSEC's training and testing facility; and developed and revised standards and codes governing installation and operation of PV systems—the National Electrical Code, IEEE, IEC, and UL PV standards.

Models such as the system performance model and the energy-based performance model developed within the program help designers and consumers. For example, estimating the amount of electrical energy produced by a grid-connected crystalline silicon solar electric system is easier for users because of PVWATTS v.2, released in FY 2001. PVWATTS simulates performance in a specific location and displays the results, showing monthly

Sandia/PIX10810

Technicians at FSEC take I-V curves of modules on the Module Long-Term Exposure Test Program. This work helps the PV industry understand performance degradation rates of modules.

and annual electrical production in kilowatt-hours and the value of that energy based on local electrical rates. From an electronic map on a Web site, the user selects the grid cell containing the proposed location of a solar electric system. Then the user specifies the parameters of the proposed system or accepts default values embedded in the software. In related work, an interactive atlas that accesses multiple databases of solar radiation data in the United States and solar collector performance can be used by those interested in non–grid-connected solar electric systems.

Another tool that architects can use to size PV systems for grid-connected applications, Energy-10, was released for review in FY 2001. The tool, which calculates hourly electrical load for a building, will encourage architects to evaluate PV for building systems during the early design stages.

The true costs of operating and maintaining PV systems are being determined by Sandia and its partners at the Southeast and Southwest Region Experiment stations, FSEC, and New Mexico State University's SWTDI. The database of actual costs will allow analysts to identify opportunities to reduce costs over the lifetime of a PV system.

Domestic Markets for Solar Electric Systems

The domestic market for solar electric systems has grown and shifted. In analyzing successful projects and those that became stalled, analysts in the NCPV have identified technical and organizational barriers to wider use of PV. The PV Subprogram works to remove these barriers by demonstrating the benefits of PV, establishing successful organizational strategies, and getting out the word that solar electric systems are viable options for many power-generation needs.

These analysis efforts help get the message to consumers. One of these activities is the PV Value Connection Matrix, which enables stakeholders to make choices based on value rather than on the current cost of conventional energy. The analysis incorporates the value-adding features of PV, such as its ability to generate highly reliable power and emergency backup power.

> *People have become more and more concerned about the cost and availability of energy. They demand to know where it comes from, how it was made, and what are the long-term implications of its use.*
> Chet Farris, Chief Operating Officer,
> Siemens Solar Industries

PV in Buildings

The PV industry roadmap predicts a major role for solar electric systems distributed throughout a utility service area, especially in commercial and residential buildings. Heeding the prediction of the PV industry, the NCPV and DOE convened a workshop to develop an R&D strategy for PV in buildings. Participants from the PV industry, the building industry, the utility sector, national laboratories, and DOE worked to develop goals for R&D, as well as activities to support market growth, to address technical and organizational barriers, and to measure success. The process of refining these goals will continue into FY 2002.

Making way for new strategies, the phased research and product development program known as PV:BONUS was nearing completion in 2001. Initiated in 1993, this was the first DOE effort to foster the development of products for the building industry that included photoelectric conversion features. The project conducted competitive solicitations that resulted in 38 partnerships and 10 new products for the residential and commercial buildings market. Partnerships that brought products to market included members with knowledge of the building industry, as well as photovoltaics, who worked together to design, develop, and manufacture the products. Knowledge of building trade practices was invaluable for designing many of the products, and building code compliance also proved essential.

Building on the experience of PV:BONUS, the DOE Solar Buildings Subprogram is trying to reduce peak electrical demand from buildings through its Zero-Energy Buildings initiative. The initiative promotes combinations of solar energy technologies and

Byron Stafford/PIX10727

Arden Realty Company of Fountain Valley, California, purchased this 240-kW PV system from PowerLight Corporation for its company headquarters. In addition to lowering the company's electric utility bills, the PV system with batteries supplies emergency backup power if the utility system goes down.

energy-efficient construction techniques to create a new generation of cost-effective buildings that can produce their own energy from renewable resources. In FY 2001, the first four contract awards for the Solar Buildings Subprogram for residential construction were made. The PV Subprogram supports the technical selection and monitoring of contracts that include solar electric elements.

An overarching effort to reduce the energy consumed by the buildings sector in the United States, the Million Solar Roofs Initiative, advances the use of solar thermal and solar electric technologies by developing partnerships. In FY 2001, the NCPV continued to work with communities by responding to requests for technical expertise. For example, researchers from NREL worked with communities in California, Colorado, Connecticut, Florida, Ohio, Pennsylvania, Texas, Arizona, California, Iowa, Missouri, New Mexico, and others. Turning vacant factory or housing land (brownfields) into solar manufacturing or generating plants is the objective of the Brightfields initiative sponsored by DOE. Local governments interested in Brightfields projects in several states consulted NCPV engineers. These projects involve complex organizational negotiations and take several years to set up.

Several barriers to widespread use of solar electric systems are being addressed by the Florida Solar Buildings Program. An important part of the program to promote solar water heating is the testing and certification of systems at FSEC to ensure that quality products are installed. Now the state wants FSEC to certify the performance of solar electric modules. After 18 months of consultation and measurements, FSEC and NREL engineers concluded that the solar simulator used by FSEC deserved the Class A rating necessary for certification. Engineers from Sandia have also worked closely with FSEC and the state of Florida to address issues of certification, including training of installers, inspectors, and maintenance personnel.

Byron Stafford/PIX09429

This Solar Independence exhibit at the Chicago Museum of Science and Industry demonstrated the basics of PV to more than 10,000 people during the summer of 2001.

Demonstrating commitment to renewable energy, the Federal Energy Regulatory Commission, the Department of the Interior, the Western Area Power Administration, and NIST worked with NCPV engineers to write specifications, place orders, and install solar electric systems at their buildings. For such buildings, NCPV staff at NREL are monitoring four commercial building PV systems and

Successful Completion of TEAM-UP

Created in 1992, TEAM-UP (Technology Experience to Accelerate Markets for Utility Photovoltaics) was a partnership between DOE and the utility industry to help develop commercial markets for a wide range of solar electric tech nologies. The TEAM-UP program has issued funding awards to 36 teams to install more than 7.4 MW of solar electric systems in more than 1,100 installations in 34 states across the United States. Private funds support the ventures at a cost-share ratio of four dollars of private funds to every dollar of DOE funds. In FY 2001, the project continued technical and financial monitoring and documentation of the 36 TEAM-UP ventures.

Plympton/PIX10729

This 2.4-kW solar electric system installed on the headquarters of the Federal Energy Regulatory Commission produces 3,600 kWh of electricity per year that are used exclusively by this building.

developing a protocol for summarizing their installation, performance, operation, maintenance, and optimization issues.

PV for Rural Utilities

There is a huge potential market for installing solar electric systems as an alternative to upgrading aging power lines to existing electric water pumps. If 5% of all applications in the rural electric cooperative system were replaced with PV, the market would equal 50 MW. Barriers to this large potential market for PV systems are being addressed when NCPV personnel provide analysis and technical assistance to organizations such as the U.S. Department of Agriculture's (USDA) Rural Utility Service, the U.S. Department of Defense, the U.S. Agency for International Development, the Florida Solar Buildings Program, the U.S. Bureau of Reclamation, Mexico's Agricultural Secretariat, the Salt River Project, and the Navajo Tribal Utility Authority (NTUA).

For example, NTUA offers skid-mounted, stand-alone home power systems on a lease-purchase agreement to residents in its service territory. To expand awareness of the program, the utility asked engineers from Sandia and SWTDI to conduct a community end-user training session for those who have systems and those who are interested in joining the program. Engineers from Sandia also conducted a 2-day workshop for NTUA electricians, engineers, and customer service personnel to train additional individuals to maintain the growing number of home solar electric systems being installed on the Navaho Reservation.

International Markets for Solar Electric Systems

The increasing demand for electricity in the developing world presents a huge potential market for solar electric products manufactured in the United States. To help U.S. companies compete internationally, the PV Subprogram supports efforts to get initial projects under way. For the first projects, it is crucial to have correct technical specifications as well as realistic ownership, financing, and maintenance strategies. Support such as training and technical assistance in Bolivia, Brazil, China, Ghana, Guatemala, Honduras, India, Indonesia, Kenya, Mexico, Morocco, Nigeria, Pakistan, the Philippines, Russia, South Africa, and Venezuela has helped U.S. companies make inroads into this growing market.

Sandia/PIX10764

The Navajo Tribal Utility Authority and Sandia conduct a training session at the Kayenta District, Navajo Nation, Arizona. Most of these potential users of solar electric systems among the Navajo community currently live without the benefit of electricity from a utility grid.

India

In 1994, DOE/NREL signed an agreement with India to help install about 300 solar electric systems for homes in remote locations of the Sunderbans region. By the close of 2001, more than 3,000 home power systems had been sold in the region. In the next 3 to 5 years, with financing from the World Bank, an additional 50,000 systems will be operating there. Much of the success of this project, designed to introduce the benefits of using solar electric systems, is attributed to the quality of the initial installations, the training given local technicians, and the follow-up replacement of any components that fail.

China

In 1995, the U.S. Secretary of Energy signed a protocol agreement with the State Science and Technology Commission of China. Since that time, the NCPV has supplied technical assistance, training, and deployment support for numerous projects in China. As a result of this long-standing collaboration and support, administrators and technicians from various organizations—from ministries to local development groups—in China visit the NCPV for briefings on PV and other renewable energy technologies.

Mexico

Since 1991, the government of Mexico's rural electrification program has led to the installation of thousands of PV lighting and PV water-pumping systems. Through Sandia, the PV Subprogram has encouraged the consideration of solar-generated electricity by providing technical assistance to nongovernmental and governmental organizations in Mexico. The objectives have been to ensure proper technical specification of systems, quality installation, and establishment of viable ownership and maintenance strategies. Successful projects have led to World Bank loans and Global Environmental Facility grants for more solar electric systems. In 2001, Sandia distributed a CD guide in Spanish for PV water-pumping projects. Data from many systems in Mexico are supplementing the reliability database maintained at Sandia.

William Wallace/PIX10729

Dr. William Wallace, on leave from NREL, is working with the United Nations Development Program Office. He was awarded the prestigious Chinese National Friendship award for his work to promote PV and other renewable energy technologies in China.

Outreach Activities

Information from DOE's Solar Program is directed at many audiences and distributed through many channels. From highly technical research reports and journal articles to fact sheets and educational materials for architects, school- children, and zoning officials, information from the program improves understanding of the characteristics and benefits of using PV to generate electricity.

In FY 2001, *The Solar Way: Photovoltaics on Indian Lands* documents how solar electricity is in harmony with the Native American philosophy that the impact of any activity should be considered for seven generations to come. Another outreach tool, an interactive CD, contains photos of PV installations in each of the 50 states. Activities in solar electric research were reported each quarter of the year in the *Solar Electricity* newsletter.

Sandia/PIX10811

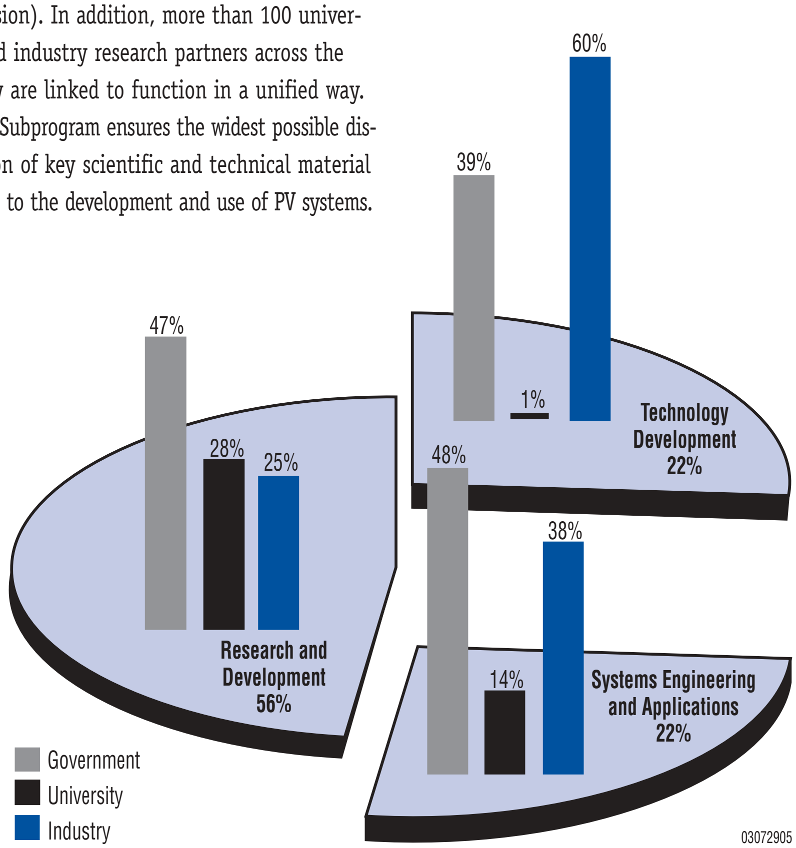
The 50 families in El Fortin, Honduras contributed to the construction of this PV water-pumping project and pay monthly fees to a bank account to cover future maintenance costs. This project, completed with local partners, Sandia, and the United Nations Food and Agriculture Organization has already inspired several other projects in rural Honduras.

Resources

The DOE PV Subprogram, as described in the 2000 to 2004 Five-Year Program Plan, conducts its business through the NCPV, an alliance of organizations working to help the U.S. PV industry maintain its global leadership position. To reach the milestones listed in the NCPV's 5-year plan and annual operating plan, the PV Subprogram relies on the core expertise of NREL and Sandia to create, develop, and deploy PV and related technologies. The NCPV also draws on the resources of Brookhaven National Laboratory, two Regional Experiment Stations (FSEC and SWTDI), and DOE's Centers of Excellence in PVat the Georgia Institute of Technology and the University of Delaware (the Institute of Energy Conversion). In addition, more than 100 university and industry research partners across the country are linked to function in a unified way. The PV Subprogram ensures the widest possible distribution of key scientific and technical material relating to the development and use of PV systems.

To serve industry, the DOE Solar Program maintains world-class facilities and researchers at the national laboratories. The national laboratories involved in the program offer the following capabilities.

- Solid-state spectroscopic analysis, experiments with photoelectrochemical processes, and applications of advanced theoretical and computational tools for predicting the behavior of PV materials
- Analytical microscopy, electro-optical characterization, surface and interface analysis of materials, analysis of cell and device operation, computer modeling of system and component performance, and development of special measurement techniques and instruments



The NCPV awards most of its federal funds through competitive procurement to industry, universities, and other research centers around the country. The federal funds for FY 2001 totalled $75.06 million.

- User-accessible laboratories for fabricating and evaluating solar electric technologies and for developing and characterizing balance-of-systems components such as charge controllers and inverters
- Outdoor test beds, indoor laboratories, and field trials for simulated, accelerated, and actual outdoor test conditions, and for varying temperature, humidity, precipitation (including hail), voltage, and radiation levels. "Global" reference conditions are typically used, but any reference set required by a university or industry client can be employed. Two general types of measurement are made: (1) Spectral response (SR) is a measure of the efficiency with which a device converts incoming narrow bands of irradiance to electricity. It is measured in terms of quantum efficiency. (2) Current versus voltage (I-V), or output performance measurements, include the open-circuit voltage of cells or modules, their short-circuit current, fill factor, maximum power output, the voltage and the current at maximum power, and the conversion efficiency. Dark I-V measurements determine diode properties and series and shunt resistances.
- Measurement systems traceable to world standards to characterize solar resources, including electronic data sets, maps, and models; and satellite imagery, meteorological data, and models.

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